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Estimated Average Annual Radon-222 Concentrations Around the Former Uranium Mill Site in Shiprock, New Mexico

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ESTIMATED AVERAGE ANNUAL RADON-222 CONCENTRATIONS AROUND THE FORMER URANIUM MILL SITE IN SHIPROCK, NEW MEXICO

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Uranium mills, as a part of the nuclear fuel cycle, produce large volumes of wastes which contain both the long and short-lived radionuclides from the naturally-occurring uranium decay chain. A relatively short-lived member of the chain, radon-222, is a noble gas and can diffuse from the wastes and be transported from its point of origin by prevailing winds. The airborne radon-222 decays into other short-lived radioactive progeny which may result in human inhalation exposures at considerable distances from the point of origin. Since the parent of radon-222 has a half-life of 1620 years, exposure to radon and its progeny will persist for thousands of years.

This study was made to estimate the annual average radon-222 concentrations around the former Shiprock, New Mexico uranium mill site in order to identify areas which may require limited or restricted occupancy and to evaluate the effectiveness of the site decontamination activities in reducing the ambient airborne radon-222 concentrations. Using on- and off-site meteorological data and radon source term estimations, average annual radon-222 iso-concentration lines were determined by computer modeling for the mill site area. The lines were determined for both pre- and post-decontamination periods.

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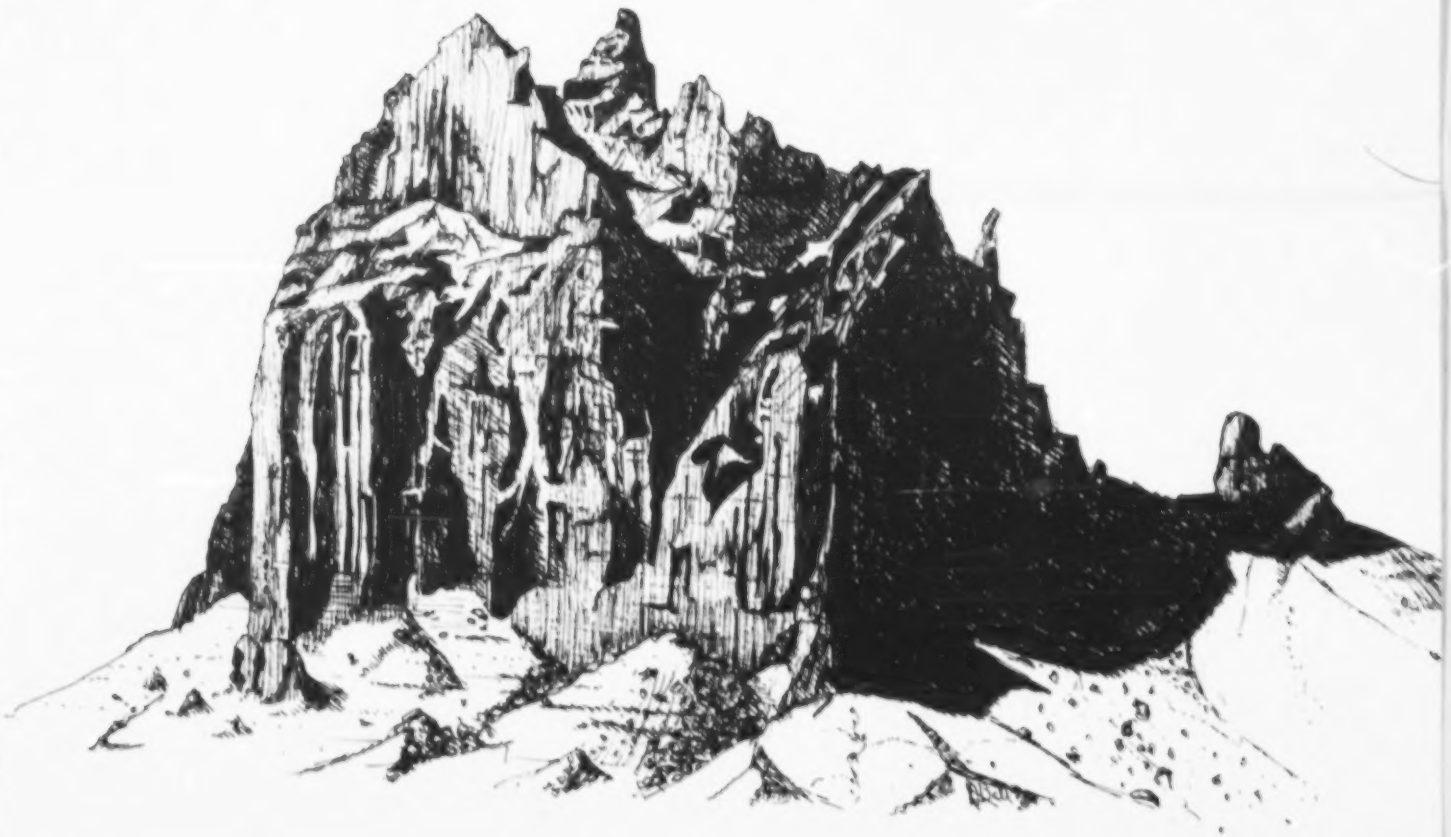

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PREFACE

The Office of Radiation Programs of the U.S. Environmental Protection Agency carries out a national program designed to evaluate population exposure to ionizing and non-ionizing radiation, and to promote development and controls necessary to protect the public health and safety. This report describes methods used to evaluate the average annual radon-222 concentrations around a former uranium mill site. It also addresses the apparent effect of mill site decontamination on the tailings piles radon-222 source term. Readers of this report are encouraged to inform the Office of Radiation Programs of any omissions or errors. Comments or requests for further information are also invited.

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Director, Office of
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ABSTRACT

Uranium mills, as a part of the nuclear fuel cycle, produce large volumes of wastes which contain both the long and short-lived radionuclides from the naturally-occurring uranium decay chain. A relatively short-lived member of the chain, radon-222, is a noble gas and can diffuse from the wastes and be transported from its point of origin by prevailing winds. The airborne radon-222 decays into other short-lived radioactive progeny which may result in human inhalation exposures at considerable distances from the point of origin. Since the parent of radon-222 has a half-life of 1620 years, exposure to radon and its progeny will persist for thousands of years.

This study was made to estimate the annual average radon-222 concentrations around the former Shiprock, New Mexico uranium mill site in order to identify areas which may require limited or restricted occupancy and to evaluate the effectiveness of the site decontamination activities in reducing the ambient airborne radon-222 concentrations. Using on- and off-site meteorological data and radon source term estimations, average annual radon-222 isoconcentration lines were determined by computer modeling for the mill site area. The lines were determined for both pre- and post-decontamination periods.

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INTRODUCTION

The Shiprock uranium mill site is located on a bench overlooking the south side of the San Juan River in the community of Shiprock, New Mexico (Figure 1). Both Shiprock and the mill site are located on the Navajo Indian Reservation.

The mill was constructed and operated from 1954 to 1963 on a leased 230-acre tract by Kerr-McGee Oil Industries, Inc. The Vanadium Corporation of America and its successor, the Foote Mineral Company operated the mill from 1963 to 1968. During its operating life, 1.5 million short tons of uranium ore were processed and approximately 3711 tons of U_3O_8 concentrate were produced and subsequently purchased by the U. S. Atomic Energy Commission.

During the milling process, the uranium ore was crushed to less than 35 mesh and acid leached to remove the uranium. Uranium was removed from the leach solution by solvent extraction and the uranium-barren solution was discharged into raffinate ponds for disposal by evaporation and seepage. The spent solids were pulped with waste process fluids and water and discharged to form tailings piles. The piles (ponds, dams) were formed with earth starter dikes and the dikes were raised using the sand fraction of the tailings. The slime fraction of the tailings was discharged into the diked impoundment.

Since only a small percentage (0.25 percent) of the ore was U_3O_8 by weight, essentially all of the ore bulk ended up as wastes. Approximately 1.5 million tons of ore were processed, resulting in approximately 1.5 million tons of wastes. The wastes contain nearly all of the radionuclides of the uranium decay chain except for most of the uranium which was removed by milling. Some carry-over of the uranium decay chain radionuclides also occurred in the barren solution.

The mill was shut down and partially dismantled before the lease expired in 1973 and the remainder of the mill and wastes (tailings) reverted back to

Figure 1. Shiprock, New Mexico and Vicinity

the Navajo Tribe which was the lessor. After expiration of the lease, portions of the mill site were occupied by the Navajo Engineering and Construction Authority (NECA). The NECA is a tribal enterprise and does construction and excavation work on the Reservation. In order to provide skilled personnel to operate earth moving equipment for both NECA and local construction projects, a heavy equipment operators training school was established on the mill site.

In November 1973, the Tribal Chairman requested assistance from the Environmental Protection Agency (EPA), Atomic Energy Commission (AEC) and the Public Health Service - Indian Health Service (IHS) concerning the stabilization of four uranium mill tailings piles on the reservation. Both the IHS and EPA responded by conducting radiation surveys to delineate the spread of wind and water eroded tailings in order that cost estimates could be made for their removal. In addition, costs were to be determined for "interim stabilization" of the tailings piles. The Shiprock site was the last of the four reservation sites surveyed (Douglas and Hans, 1975). During the survey, it was noted that the earth-moving training activities were aggravating the radiological condition of the mill site. It was recommended at that time, in April 1974, that the training activities be directed toward the decontamination of the mill site and its environs and toward the interim stabilization of the tailings piles. This would, in effect, reduce potential internal and external exposures to the Shiprock and mill site inhabitants by controlling erosion of the tailings, returning eroded tailings back to the piles, and cleaning up areas contaminated by mill processes. The decontamination work was officially started by the Tribal Vice-Chairman at ground breaking ceremonies on January 8, 1975 and is near completion.

The decontamination work is proceeding along the general outline provided in a 10-task work plan (Figure 2). The plan is being administered and executed by staff from EPA, IHS, Navajo Environmental Protection Commission (NEPC), NECA, and the New Mexico Environmental Improvement Agency (NMEIA). Environmental sampling and measuring networks have been established to document the on- and off-site radiological improvement as a result of the decontamination activities.

Major Elements of the Work Plan for Decontamination of the Shiprock Uranium Mill Site

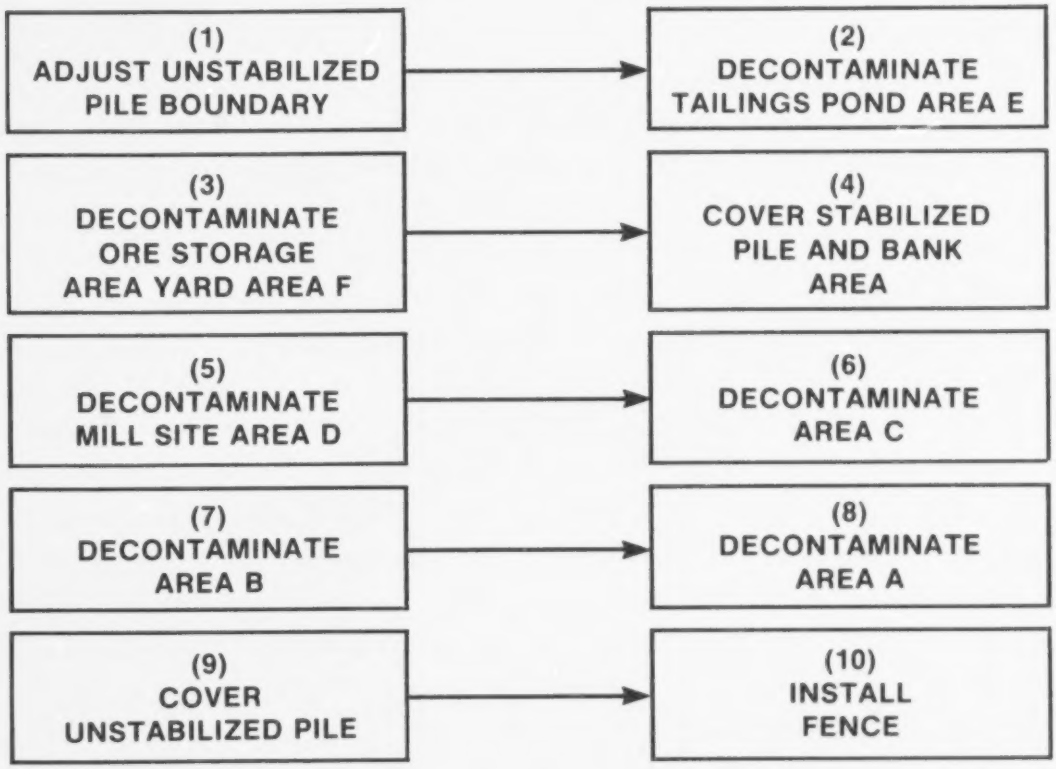

Figure 2. Major Elements of the Work Plan for the Decontamination of the Shiprock Uranium Mill Site

RADIOLOGICAL ASPECTS

A uranium mill may be considered as having four major operations. These are 1) the stockpiling and preparation of the ore for leaching, 2) the leaching of the uranium from the ore, 3) the removal and processing of the uranium from the leachate, and 4) the disposal of the liquid and solid wastes. Ore effluents and wastes from all of these operations may contribute to human exposure while the mill is operating. After the mill has ceased operating, some of the residual effluents and ore may be potential sources of exposure. Solid wastes, however, appear to constitute the principal source of exposure.

The solid wastes are disposed of by above-ground storage and the liquid wastes are commonly disposed of by evaporation and seepage which is commonly called the "crib" method. Human exposure, resulting from the waste disposal, occurs from several major sources which are listed.

1. Direct gamma radiation exposure from the tailings piles, ponds, and wind and water eroded tailings.
2. Leaching of radionuclides from the tailings piles and ponds into ground and surface water.
3. Wind erosion and subsequent deposition of tailings.
4. Diffusion of radon-222 from the tailings piles and ponds through the air - man pathway.

Environmental sampling and measurement data indicate that the decontamination of the Shiprock mill site has resulted in a reduction of potential exposures from all of the listed sources except leaching. The gamma radiation source has been reduced substantially by returning eroded tailings and ore remains back to the original tailings piles. Their placement on the unstabilized

tailings pile surface has, in effect, substantially reduced the above-ground exposure rates around and adjacent to the pile.

Substantial leaching has occurred while process fluids were being discharged on the tailings piles, in the raffinate ponds and through the plant drains (DHEW-PHS, 1960). Some small scale leaching, observed in exploratory trenches, is presently occurring to the San Juan River. The source of the water is not known and it is also not known if the interim stabilization will have any effect in diminishing the seepage.

Wind erosion of the south pile has been substantially reduced also by the placement on it of a lightly contaminated soil cover resulting from the decontamination activities. The north tailings pile was stabilized with 0.5 to 2.0 feet of pit-run soil and gravel prior to the mill closing. In addition, approximately three feet of sand and cobble was added to 40 percent of the surface area of the north pile to provide a roadbed in order to keep wheeled vehicles from sinking into the tailings while adding cover to bare areas of the pile sides. Although both of the tailings piles are covered, some minor wind erosion is probably occurring from the decontamination activities, the off-pile areas that have not been decontaminated, and from the pile covers.

Radon-222 is capable of moving through relatively large thicknesses of earth. Because of this, some fraction of the total radon produced within the tailings pile can become airborne and be transported by prevailing winds, resulting in human exposure at several miles from the mill site. Decontamination of the mill site and cover added to the tailings piles have reduced the radon-222 source term.

PURPOSE OF REPORT

The decontamination activities at the former Shiprock uranium mill site have been following a master work plan. Step 10 of the work plan is directed at designating exclusion and restricted use areas around the mill site after the decontamination and interim stabilization have been completed. The exclusion and restricted use area locations will be dependent on the residual gamma exposure rate levels, airborne radioactive particulate and radon-222 concentrations. It appears, for the most part, that the gamma exposure rates and the airborne particulates will have little influence concerning the designation of off-pile exclusion areas. Radon-222 exhalation, although reduced by the decontamination activities, is now considered to be the dominant factor for determining any exclusion areas. The primary purpose of this report is to estimate the average annual radon-222 concentrations in the local environment around the tailings piles in order that the IHS and the Navajo Tribe can determine if any exclusion or restricted-use areas should be designated in light of available radon-222 concentration guides or health risks posed by radon-222 and its progeny.

In addition to satisfying the work plan task, techniques and procedures for evaluating ambient levels of radon-222 have been developed which are applicable to other active and inactive mill sites. Some estimates of the tailings pile radon-222 source term, prior to the decontamination work, have been made. Using these and contemporary estimates, the effects of the decontamination work on the radon-222 source term can be appraised.

STUDY DESCRIPTION

With reference to the purpose of the report, radon-222 concentrations needed to be evaluated in areas around the mill site in order to determine if any measures should be taken to minimize human exposure. This means, in effect, that the average annual radon-222 concentrations in all areas adjoining the mill site should be evaluated. Assuming a constant average radon-222 source term for the tailings piles, its concentration in the adjoining areas is dependent upon local meteorological conditions. These conditions are variable from hour to hour and season to season; however, average meteorological conditions are similar from year to year. With regard to the aforementioned, the radon concentrations in adjacent areas should be determined for at least one year and preferably longer.

Two approaches may be taken to estimate the average annual radon-222 concentrations in areas around the mill site. The first is to place samplers or measuring devices in areas of interest and monitor the radon-222 levels continuously for a year, or at specific intervals throughout the year. In order to establish a distance versus concentration relationship, at least two measurements should be made at different distances along each radial from the tailings piles. The second approach is to use annual meteorological data with the tailings pile radon-222 source term and compute the average concentrations as a function of distance from the tailings piles.

The latter approach was used because of the logistics problems involved with the former approach. The latter requires an estimate of the radon-222 source term for the tailings piles, local wind speed and direction frequencies, and the frequency of the various atmospheric stability classes. In addition, an atmospheric dispersion model is needed to calculate the average annual radon-222 concentrations resulting from large area sources. Elements of the latter approach are described in further detail.

ESTIMATES OF THE RADON-222 SOURCE TERM

Decontamination of the Shiprock uranium mill site began in late 1974 and has resulted in major changes of the mill site. The changes include a major alteration in the tailings pile configuration, the removal of a former raffinate pond, and the addition of contaminated earth on the south tailings pile. The contaminated earth now covers the south tailings pile to a depth of approximately four feet. The north tailings pile cover averages one and one-half feet in depth. These changes have reduced the ambient radioactive particulate concentrations and gamma ray exposure rate levels around the mill site. Also they have apparently been effective in substantially reducing the radon-222 source term for the tailings piles.

During the very early stages of the site decontamination, radon exhalation measurements of the tailings piles were made with the barrel accumulation technique (Bernhardt, et al, 1975) and calculations using borehole logging data (Rodgers, 1977). The radon-222 source term was also estimated (Swift, 1976) using a calculation method described by Schaiger, 1974. Contemporary estimates of the source term which reflect the effect of the major changes resulting from the decontamination activities, have been made by Hans, 1977. It is not expected that any significant changes in the contemporary source term estimation will occur as a result of the remaining decontamination activities. Early and contemporary radon-222 source term estimates are listed in Table 1.

TABLE 1. RADON-222 SOURCE TERM ESTIMATES FOR THE SHIPROCK, NEW MEXICO URANIUM MILL TAILINGS PILES

Early Source Term (pCi/sec)	Method	Contemporary Source Term (pCi/sec)	Method
3.6×10^8	From exhalation data (Bernhardt, et al 1975)	2.7×10^7	Pile edge flux measurement (Hans, 1977)
2.4×10^8	From bore hole logging (Rodgers, 1977)	2.0×10^7	Downwind sampling (Hans, 1977)
2.2×10^8	Calculations (Swift, 1976)	5.8×10^7	Downwind sampling (Hans, 1977)
		2.8×10^7	Charcoal canister (FBDU, 1977)
2.7×10^8	(Average)	3.3×10^7	(Average)

The average difference between the early and contemporary source term estimates, confirmed with on-site working level measurements, is a measure of the effect of the decontamination activities.

WIND SPEED AND DIRECTION FREQUENCIES

A meteorological station was established on the mill site in 1974 in order to collect local weather information in support of the decontamination activities. The station consists of a small travel trailer and two meteorological units, each containing wind speed, wind direction, and temperature sensors. One meteorological unit is mounted on a telescoping mast at an elevation of 10 meters above the ground and the other unit is mounted at one meter above the ground. The mast of the elevated unit is attached to the trailer and the stand for the other has sufficient cabling to permit it to be located away from air disturbances that may be caused by the trailer wake. Electrical power and signal processing for the units are provided from the trailer.

Wind speed is measured with a cup anemometer and wind direction is determined with a vane. Interrogation of the wind speed and direction occurs every 15 minutes and the data are recorded on paper punch tape for computer processing.

STABILITY FREQUENCIES

Although temperature measurements are recorded for two different heights, they are not considered suitable for estimating atmospheric stability frequencies on site. Farmington, New Mexico, which lies approximately 40 km east of Shiprock, is the closest community at which long-term stability observations have been made. Farmington, like Shiprock, lies in the San Juan River Valley and is subject to down-valley winds during stable atmospheric conditions. The river valley at Farmington runs in an east-west direction, while the valley in Shiprock runs southeast to northwest. Stability frequencies for Farmington were acquired from the National Climatic Center, Asheville, North Carolina.

DISPERSION MODEL

In order to estimate annual average radon-222 concentrations around the Shiprock tailings piles, the source term and meteorological parameters must be incorporated into an atmospheric dispersion model. Models exist for dispersion calculations, however, most of them are derived for point-source releases. Unfortunately, tailings piles constitute large area source releases and are not readily amenable for point-source calculations except at large source to receptor distances. A computer code, "Area Source Radiological Emission Analysis Code (AREAC)" was developed by EPA for such uses (Michlewicz, 1976). The code was specifically written to accurately assess close-in air concentrations resulting from a large area source such as a uranium mill tailings pile.

The EPA area source computer model (AREAC) takes into account parameters such as an area source shape, cloud dispersion, ground and inversion-lid reflections and radionuclide decay by time of flight. Several simplifying assumptions were made concerning the source and are listed:

1. A circular tailings pile configuration was assumed with an equivalent area of the tailings piles (Figure 3)
2. The radon-222 source is uniformly distributed within the tailings pile
3. The radon-222 release rate is constant
4. The radon-222 concentrations are average over each sector for a given distance downwind
5. A ground level release of radon-222 is assumed.

In this application, the circular equivalent area was divided into 100 point sources and the radon-222 concentration due to each source was summed at the desired downwind distances. A standard continuous point source sector averaged Gaussian diffusion equation (Appendix) was used for the summing. Radon-222 concentrations were computed for distances along each of 16 sectors. The sectors are depicted in Figure 4.

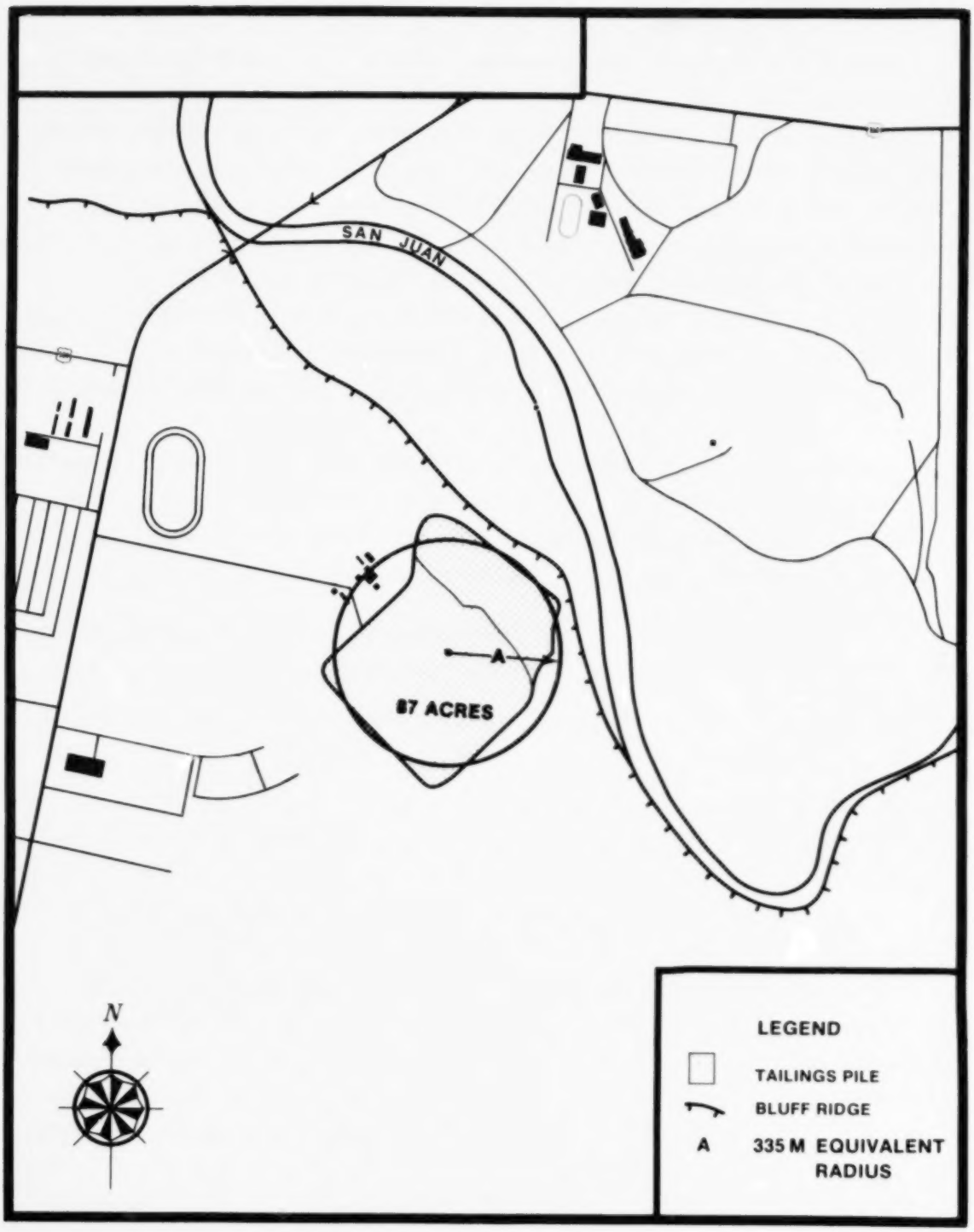

Figure 3. Equivalent Area Circle

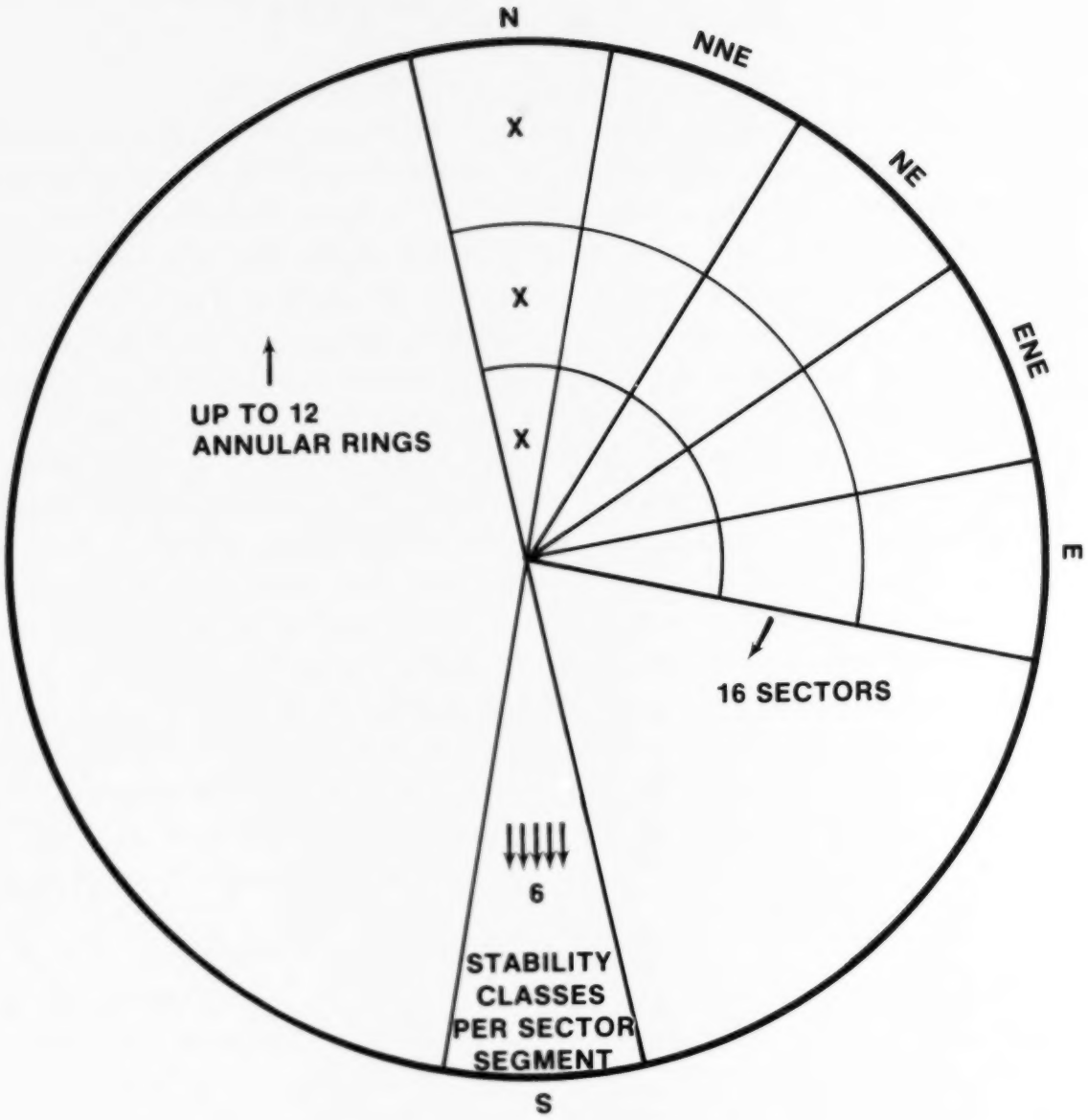

Figure 4. Geometry of AREAC - Plan View

STUDY RESULTS

A summation of the local meteorology is given in Table 2, i.e., wind speed classes versus wind direction or the joint frequency distribution summed over all stability classes for the Shiprock on-site data. Calms (0 to 1 miles per hour) were distributed proportionally in the lowest wind speed class (1-3 miles per hour), resulting in a 0-3 miles per hour wind speed class. The resulting wind frequency distributions, using on-site data for Shiprock and Farmington, New Mexico is presented in Table 3. The Farmington airport, which is about 40 km (25 mi) east of Shiprock was the nearest station collecting meteorological data available for comparison with the Shiprock data. Both Farmington and Shiprock lie in the San Juan River Valley; however, the valley runs east to west in the Farmington area and southeast to northwest in the Shiprock area. In addition, the valley is generally steeper in the Farmington area. Because of these topographical differences, the wind frequency distributions for both locations are somewhat different. The down-valley winds, which are generally associated with stable conditions, are spread through the west to north-northwest sectors in Shiprock while they are spread through the southwest to west-northwest sectors in Farmington. This reflects the differences in the San Juan River Valley directions at these locations. The same directional frequencies are more pronounced for the Farmington area than the Shiprock area. This is probably due to the differences in the valley slopes at the two locations.

Unfortunately, the on-site meteorological data does not include stability information. Consequently, the overall stability distribution for the Farmington airport (Table 4) has been applied to the joint frequency distribution (Table 2) to simulate a joint frequency distribution versus stability type for Shiprock. The overall stability distribution for Shiprock probably does not vary much from that of the Farmington airport.

Radon-222 concentrations were calculated for distances of 435 m to 72 km from the center of the tailings piles for two different radon-222 source terms. This was done to illustrate the effects of decontamination of the mill

TABLE 2. SHIPROCK JOINT FREQUENCY DISTRIBUTION (10 m Level)
WIND SPEED CLASS (MILES PER HOUR)

WIND DIRECTION (Towards)	0 - 3	4 - 7	8 -12	13 - 18	19 - 24	Over 24
S	.00824	.00540	.00244	.00049	.00034	.00003
SSW	.00620	.00336	.00102	.00049	.00022	.00003
SW	.00864	.00627	.00232	.00034	.00015	.00000
WSW	.01630	.01753	.00963	.00262	.00015	.00006
W	.02581	.03788	.03016	.00710	.00105	.00006
WNW	.03251	.06019	.02828	.00624	.00213	.00025
NW	.02945	.06538	.02806	.00432	.00179	.00040
NNW	.01735	.02581	.01213	.00355	.00170	.00065
N	.01371	.01043	.00617	.00204	.00185	.00034
NNE	.01173	.00818	.00800	.00383	.00228	.00068
NE	.01469	.01272	.01278	.00883	.00596	.00225
ENE	.01710	.01719	.00929	.00577	.00478	.00139
E	.01945	.02772	.01809	.00997	.00562	.00120
ESE	.01735	.02729	.02738	.02081	.01482	.00491
SE	.01454	.01935	.01954	.01398	.00917	.00445
SSE	.00957	.00858	.00633	.00225	.00086	.00025

TABLE 3. WIND FREQUENCY DISTRIBUTION (PERCENT)

Wind Direction (Towards)	Shiprock (On-site Data)	Farmington Airport
N	3.45	3.79
NNE	3.47	2.82
NE	5.72	5.71
ENE	5.55	7.02
E	8.21	12.87
ESE	11.26	6.07
SE	8.10	2.80
SSE	2.78	1.88
S	1.69	4.38
SSW	1.13	4.82
SW	1.77	9.18
WSW	4.63	10.02
W	10.21	16.35
WNW	12.96	6.64
NW	12.94	3.63
NNW	6.12	1.96

TABLE 4. ATMOSPHERIC STABILITY DISTRIBUTION FOR THE FARMINGTON, N.M. AIRPORT

Stability Class	Stability Description	Frequency (Percent)
A	Extremely unstable	4.68
B	Moderately unstable	8.74
C	Slightly unstable	12.96
D	Neutral	15.81
E	Slightly stable	12.73
F	Moderately stable	45.08

site on the source term as well as depict the prevailing radon-222 concentrations that will occur after the site decontamination has been completed. The estimated radon-222 source term before decontamination began was 8500 Ci/yr and 1040 Ci/yr after decontamination has been completed. Iso-concentrations of radon-222 versus distance in each sector for pre- and post-decontamination conditions are tabulated in Tables 5 and 6.

Figure 5 locates radon iso-concentration lines around the mill site on a local map for the pre-decontamination period. The 1 pCi/l iso-concentration line (Figure 5) extends for a distance of 1500 m (∿1 mile) to the northwest of the mill site and reaches into the more heavily inhabited areas. The 3 pCi/l iso-concentration line extends off-site from the south-southwest to the north-northwest sectors and encompasses only very lightly inhabited areas. Only a small projection of the 10 pCi/l iso-concentration line could be made to the northwest area. This line is on-site and is located close to the tailings piles.

Figure 6 locates iso-concentration lines on a local map for the post-decontamination period. In Figure 6, the 0.1 pCi/l iso-concentration line is well off-site, extending into the more heavily inhabited areas from the southwest to the north-northwest sectors. The 1 pCi/l iso-concentration line is located on-site except for a small area on the southwest corner. A 3 pCi/l iso-concentration line could not be plotted.

TABLE 5. RADON-222 ISO-CONCENTRATION DISTANCE (m) for EACH SECTOR (PRE-DECONTAMINATION)

	CONCENTRATION (pCi/l)				
Sector	10	1	0.1	0.01	0.001
N		800	3,300	15,000	
NNE		800	3,000	14,000	
NE		920	3,700	17,500	
ENE		1,000	3,900	19,000	
E		1,100	4,700	22,500	
ESE		1,125	4,900	23,000	
SE		980	4,000	19,000	
SSE		760	2,700	12,000	66,000
S		620	2,300	9,800	54,000
SSW		600	1,900	8,200	42,000
SW		700	2,350	10,700	56,000
WSW		1,000	3,800	18,000	96,000
W	410	1,325	5,600	28,000	
WNW	420	1,575	6,700	34,000	
NW	400	1,500	6,600	32,000	
NNW	380	1,025	4,200	20,000	

TABLE 6. RADON-222 ISO-CONCENTRATION DISTANCE (m) for EACH SECTOR (POST-DECONTAMINATION)

	CONCENTRATION (pCi/l)				
Sector	1.0	0.1	0.01	0.001	0.0001
N		900	3,550	17,500	
NNE		900	3,500	16,000	
NE		970	4,200	20,000	
ENE		1,125	4,500	22,000	
E	400	1,280	5,300	26,500	
ESE	375	1,280	5,400	27,500	
SE		1,100	4,500	22,000	
SSE		830	3,100	14,000	76,000
S		670	2,550	12,000	62,000
SSW		640	2,100	9,100	48,000
SW		780	2,700	12,000	63,000
WSW	370	1,100	4,300	20,500	
W	460	1,500	6,500	32,500	
WNW	470	1,750	7,600	40,000	
NW	460	1,700	7,600	38,000	
NNW	400	1,200	4,800	23,000	

Figure 5. Radon-222 Iso-Concentration Lines in the Vicinity of the Shiprock, New Mexico Uranium Mill Tailings Pile (Pre-Decontamination)

Figure 6. Radon-222 Iso-Concentration Lines in the Vicinity of the Shiprock, New Mexico Uranium Mill Tailings Pile (Post-Decontamination)

DISCUSSIONS AND CONCLUSIONS

CONTEMPORARY RADON-222 CONCENTRATIONS AND HEALTH EFFECTS RISKS

The decontamination activities at the former uranium mill site in Shiprock, New Mexico are proceeding into the final stages of the overall work plan. One final task in the work plan is to determine what areas, if any, should be restricted around the mill site because of radon-222 exhalation from the tailings piles.

Current regulations and guides concerning radon are excerpted (Swift et al., 1976):

> "Federal regulations 10 CFR, Part 20 presently permit AEC-licensed operations to release average concentrations of radon-222 to the air in unrestricted areas of 3×10^{-9} μCi/ml, (3 pCi/l) above natural background. (Such releases may be subject to reduction if it appears that a suitable sample of an exposed population may have an intake of the decay product radionuclides greater than they would have if exposed to average concentrations of one-third of the 3×10^{-9} μCi/ml (1 pCi/l).)"

> "Recommendations of the International Commission on Radiological Protection (ICRP) state that the annual radiation dose limits for individual members of the general public should be one-tenth of the corresponding annual occupational dose for continuous exposure as listed in the Committee II report. Application of these recommendations to the 168 hour concentration (10 pCi/l) for occupational exposure to radon-222 (with daughter products present at equilibrium concentrations) leads to a value of 1 pCi/l for continuous exposure to individuals in the general population."

Since the Shiprock mill site's Atomic Energy Commission license has been terminated, the radon-222 concentrations stated and discussed in the excerpt do not have a legal status and can only be used for planning and guidance.

Although radon-222 is an alpha emitter and is respirable, its contribution to a respiratory tract dose is relatively negligible when compared to its short-lived progeny. A majority of the epidemiological evidence relating lung cancer with exposures to radon-222 and its progeny has been made with the unit of working level (WL) instead of the usual radiological units of rems or rads and present regulations and guides use this unit. Table 7 lists conversion factors and equivalents for radon-222 and progeny.

TABLE 7. CONVERSION FACTORS AND EQUIVALENTS FOR RADON-222 AND PROGENY

1. One working level is equal to a combination of short-lived radon daughters in one liter of air that will result in an ultimate emission of 1.3×10^5 MeV of alpha energy.

2. A working level month (WLM) is the exposure to one WL concentration of radon daughters for 173 hours or an equivalent product of radon daughter concentrations and time.

3. Assumed radon-222 and daughter ratios for a living accommodation with normal ventilation (1.0/0.9/0.5/0.35).

4. Continuous exposure to 1 pCi/m^3 of radon-222 $\simeq$ Continued exposure of 5×10^{-6} WL

5. $1 \frac{WL}{Year}$ = 25 WLM for the general public (USEPA, 1978)

6. A continuous exposure of one WLM is assumed to increase an individual's bronchial cancer risk by three percent.

Occupied structures on the mill site lie close to the 1 pCi/l iso-concentration line. Occupancy of the permanent structures is generally limited to normal working hours (40 hrs/week) or about 23 percent of full occupancy. This would amount to about an average effective exposure to 0.23 pCi/l of radon-222. Since the occupancy is also limited to daylight hours, the effective radon exposure will be less because stable atmospheric conditions occur less frequently during the daylight hours.

Figure 7 depicts contemporary iso-risk rate locations based on radon iso-concentrations around the mill site. The risks were calculated using conversion factors and equivalents for radon-222 and daughters and are listed in Table 7. The results of the risk calculations are contained in Table 8.

The iso-risk line values indicated in Figure 7 are contemporary annual risks and must be multiplied by the number of years that an individual will be exposed to the risk. For example, if an individual lives on the 0.39 percent risk line for 10 years, his relative bronchial cancer risk will be increased by (0.39%/yr x 10 years) or 3.9 percent.

Presently the 0.39 percent risk per annum iso-risk line (1 pCi/l) extends, at its most distant point, about 180 m (600 ft) in the northwest direction from the tailings piles and it is well within the mill site boundaries in the northwest quadrant. It does, however, extend off-site for a distance of approximately 60 m (200 ft) in the southwest quadrant Figure 8. An area approximately 30 m (∿100 ft wide) adjacent to the southwest edge of the pile is taken up by a haul road.

Other sampling, conducted on the mill site, tends to support the annual average radon-222 concentrations estimated with AREAC. This sampling was made to determine working level values in the NECA office and the new maintenance shop building. Twenty-six working level samples were taken in the office building during the period of January through October, 1977. The average net working level was 0.007. Using the previously described conversion factors, this would correspond to an outdoor average radon concentration of approximately 1.4 pCi/l. The average net working level for the shop was 0.0035 for the same time period the office building was sampled. Using the conversion

Figure 7. Contemporary Health Effects Risks Around the Former Uranium Mill Site at Shiprock, New Mexico

TABLE 8. ISO-RISK RATE CALCULATIONS BASED ON ISO-CONCENTRATIONS USING CONVERSION FACTORS AND EQUIVALENTS (TABLE 7)

Iso-Concentration (pCi/l)	WL*	WLM/YR	Percent Relative Risk Increase Per Year
1	5×10^{-3}	0.13	0.39
0.7	3.5×10^{-3}	0.088	0.26
0.3	1.5×10^{-3}	0.038	0.11
0.1	5×10^{-4}	0.013	0.039

* Assuming 50 percent equilibrium.

factor as before, this would correspond to an outdoor average radon concentration of 0.7 pCi/l. Both buildings are close to each other and they are about the same distance from the tailings piles. The probable reasons that the office building has approximately twice the WL of the shop are that the office was built at the beginning of the milling activities and tailings have been tracked into it over a longer period of time by the former operators as well as NECA staff. Some radium-226 is known to be entrained in the office carpeting and a planter, containing approximately two cubic yards of tailings, was located against the office outer wall.

The outdoor radon concentrations for the two buildings were calculated based on the conversion factor which assumes 50 percent equilibrium ratio.* Outdoor radon-222 measurements were made concurrently with indoor WL measurements for the office building during a 24-hour period on February 28, 1976 (FBDU-1977). The results of these measurements indicates that the relationship between outdoor radon and indoor WL is that 1 pCi/m^3 corresponds to approximately 1.8×10^{-6} WL (18 percent equilibrium ratio). Using this relationship with the net long term WL measurements, the average outdoor radon-222 concentrations would be approximately 4 pCi/l. The outdoor radon concentration estimated from WL measurements in the shop would be 2 pCi/l using the FBDU data. It is believed that the shop is more representative of actual WL than the office for reasons previously cited. It is also assumed that the lower equilibrium ratio derived from the FBDU-1977 report data is due to less radon daughter ingrowth because of the short distance between the office building and the tailings piles. Further discussion of the two equilibrium ratios is contained in the next section concerning pre-decontamination radon-222 concentrations.

PRE-DECONTAMINATION RADON-222 CONCENTRATIONS

With reference to Figure 5, it would appear that during the latter part of the milling activities the annual average radon-222 concentrations beyond the boundry of the mill site may have exceeded the Atomic Energy Commission's Regulations (USAEC, 1965).

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* Percent equilibrium equals the working level divided by the ambient radon concentration divided by 100 pCi/l.

The average net working level in the NECA office from February 1974 to March 1975 was 0.025 WL. Again, using the stated conversion factor(50 percent equilibrium ratio), this would correspond to an average outdoor radon-222 concentration of 5.0 pCi/l. Using a conversion factor of 1 pCi/m^3 = 1.6×10^{-6} WL (FBDU, 1977), the average outdoor radon-222 concentrations would be ∿14 pCi/l. Both of these concentrations could be adjusted downward by ∿1 and 2 pCi/l respectively, because of internal and external contamination of the office building.

Some short-term (Nov. 1974-Feb. 1975) WL measurements were made at three locations during the pre-decontamination period near the intersection of the 1 pCi/l iso-concentration line and U.S. route 666 and in the west-southwest sector (Figure 5). The net average WL for the three locations was 0.0017 WL. Using the 50 percent equilibrium ratio, this would correspond to an average outdoor radon-222 concentration of 0.3 pCi/l. The 18 percent equilibrium ratio would yield ∿1.0 pCi/l.

Two other locations were also measured for a short duration (Dec., 1974-March, 1975) for WL. These locations are west-northwest of the mill site on the west side of U.S. route 666. The average net WL for the two locations was 0.0037 WL. Using the EPA conversion factor, the average radon-222 concentration would be ∿0.7 pCi/l. The FBDU conversion factor would yield approximately 2 pCi/l of radon-222. The pile center to location distance is approximately 1300 m. The AREAC yields approximately 1.4 pCi/l at this distance.

It appears, based on the limited WL measurements, that the outdoor radon-222 concentration to WL relationship (1 $pCi/m^3 \simeq 1.6 \times 10^{-6}$ WL) estimated from on-site measurements (FBDU-1977) fits the AREAC model data reasonably well.

The addition of the earth blanket, resulting from the decontamination activities, on the south tailings pile and riprap placed on the north tailings pile appear to have reduced the radon source term to about 12 percent of its original estimated value (Table 1). The WL measurements in the office building, adjusted for the contaminants, indicates that the source term probably has been reduced to 16 percent of its original value.

ESTABLISHMENT OF EXCLUSION OR RESTRICTED AREAS

Since the site is largely decontaminated and if a guide of 1 pCi/l average annual concentration of radon-222 is applied to the area around the tailings piles, all areas with radon-222 concentrations equal to or greater than 1 pCi/l will lie within the confines of the mill site boundary (Figure 8) except for a small area to the southwest of the tailings piles. The occupied buildings on site probably experience an average annual concentration of radon-222 of approximately 1 to 2 pCi/l. It is likely that, if the site occupancy of the general area around and including the office, workshop and classroom is limited to normal working hours, the average exposure to individuals will be less than 1 pCi/l radon-222. Occupancy of any areas near the southwest corner of the tailings piles would be unlikely because of the heavy equipment traffic on the haul road.

With regard to working level guidance, the Public Health Service Surgeon General's Guidelines for Grand Junction, Colorado (U.S. DHEW, 1960) stipulate that remedial action should be considered for structures that have mill tailings use when their average WL ranges from 0.01 to 0.05. Remedial action is necessary when WL are $\geq$0.05.

The EPA Office of Radiation Programs is preparing WL guidance concerning the Florida phosphate industry (USEPA, 1978). These guides take into account more recent data and information and they may be used for guidance concerning non-occupational exposures around uranium mills as well as other sources of radon progeny exposures. The guides stipulate that the WL in frequently occupied buildings is unacceptable if the gross WL is $\geq$0.03. Working levels ranging from 0.005 WL above ambient background to a gross WL of 0.03 should be reduced to levels as low as reasonably achievable.

With regard to the EPA guidance, the new shop and office building net working levels are 0.0035 and 0.0070 respectively. Although the office building exceeds the lower level of the guides, its occupancy factor is 23 percent as compared to an occupancy factor of 80 percent on which the guides are based.

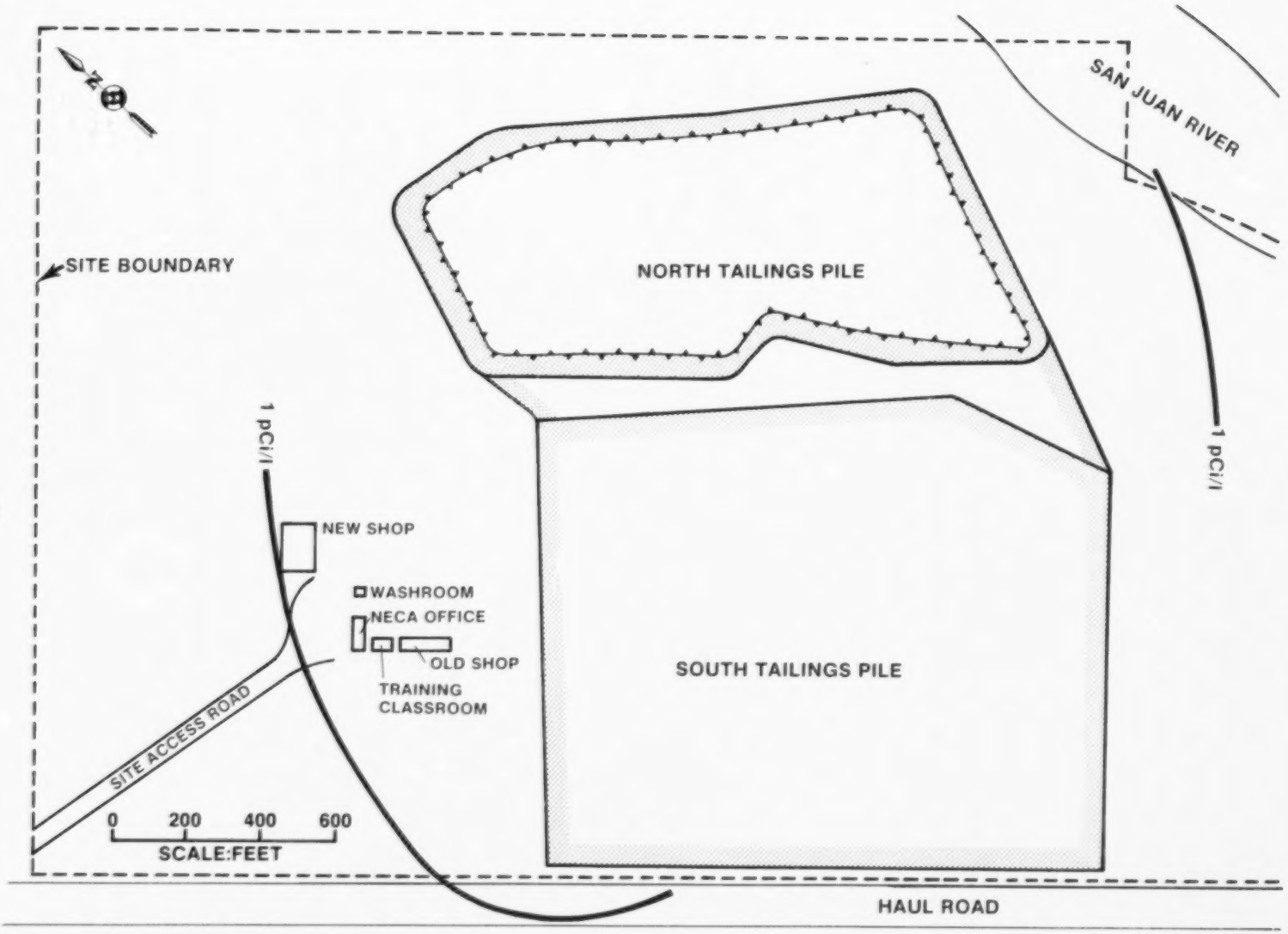

Figure 8. Radon-222 Iso-Concentration Line Location (1 pCi/l)

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APPENDIX

Continuous Point Source Sector Averaged Gaussian Diffusion Equation

$$\bar{\chi}_i = 2.032\, Q \frac{\sum_{j=1}^{6} F_{ij} \exp\left(\frac{-h^2}{2\sigma_{zj}^2}\right)}{\bar{u}_{ij}\, \sigma_{zj}\, x}$$

Where: $\bar{\chi}_i$ = ground level concentration for the i th sector (Ci/m^3)

Q = source release rate (Ci/sec)

F_{ij} = fractional wind frequency in the i th sector for the j th stability class

x = distance downwind (m)

h = effective release height (m)

σ_{zj} = standard deviation of the vertical distribution of an assumed Gaussian plume for the j th stability class (m)

$\bar{u}_{ij}$ = average wind speed in the i th sector for the j th stability class (m/sec)